Dual-band Inverted-F MIMO Antenna Using Enhanced Hummingbird Algorithm for Mobile Phone Terminals

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***Abstract*—The design and optimization of a high-performance, dual-band 4-element Multiple-Input Multiple-Output (MIMO) antenna system targeting the 5G NR n78 and 5.8 GHz ISM bands is presented in this work. The design process utilizes the Enhanced Artificial Hummingbird Algorithm (enAHA), a recently developed nature-inspired metaheuristic optimization algorithm. The enAHA is employed to optimize nine geometric parameters of a modified Inverted-F antenna (IFA) with a folded arm. The full 4-element MIMO system, measuring a compact 42 mm x 87 mm, demonstrates robust isolation with S_{ij} parameters maintained below -20 dB. Computed results indicate peak gains of 2.63 dBi and 4.71 dBi, with radiation efficiencies of 87% and 99% in the respective frequency bands. Furthermore, the diversity performance is validated through well-known MIMO performance metrics, yielding an Envelope Correlation Coefficient (ECC) below 0.02, a Diversity Gain (DG) of 9.99 dB, and a Total Active Reflection Coefficient (TARC) lower than -15 dB. These results confirm that the proposed system offers high efficiency and isolation, as well as excellent diversity characteristics, making it an excellent candidate for integration into modern mobile terminals.**

***Index Terms*—enAHA, MIMO antenna, 5G NR, ISM band, ECC, TARC, DG.**

I. Introduction

The rapid evolution of mobile telecommunications, particularly the transition toward 5G New Radio (NR) and the expansion of the Internet of Things (IoT), has necessitated the development of antenna systems capable of supporting significantly higher data rates and channel capacities. MIMO technology has emerged as a cornerstone of modern wireless standards, enabling spatial multiplexing and improved reliability through diversity [1]. However, integrating multiple antenna elements within the constrained volume of modern mobile terminals presents significant design challenges, primarily concerning mutual coupling and the degradation of diversity performance [2].

Among the many antenna designs, the Inverted-F Antenna (IFA) is still widely favored for mobile handsets due to its compact profile, straightforward design, and the ease of integration into the device chassis [3], [4], [5]. To meet the requirements of multi-standard connectivity, researchers have moved toward modified IFA structures capable of multi-band operation.

Achieving optimal performance in such complex, multi-parameter environments—where resonance and isolation must be balanced—requires advanced computational techniques. Traditional gradient-based optimization often struggles with the high-dimensional and non-linear nature of electromagnetic design. As a result, nature-inspired metaheuristic algorithms have gained considerable prominence in this field. The Artificial Hummingbird Algorithm (AHA) [6] mimics the sophisticated foraging behaviors of hummingbirds and has shown remarkable efficiency in solving complex engineering problems. By utilizing enhanced variants of such algorithms, designers can navigate the search space more effectively to achieve compact, high-performance antenna designs with effective decoupling and impedance matching.

In this work, an enhanced version of enAHA is utilized to design and optimize a dual-band, 4-port MIMO antenna system. The design features a modified IFA with a folded arm, optimized for operation at 3.55 GHz and 5.8 GHz. The optimization process focuses on minimizing return loss while maximizing isolation to ensure superior MIMO performance metrics, including the Envelope Correlation Coefficient (ECC) and Total Active Reflection Coefficient (TARC) [4], [7].

The rest of this paper is structured as follows. Section II provides a comprehensive description of the enAHA optimiza-

tion framework. Section III outlines the design parameters and optimization of the single IFA unit cell. Section IV presents the configuration of the 4-port MIMO system and analyzes the computed results, including diversity metrics. Finally, in Section V, some concluding remarks are given.

II. enAHA Algorithm Description

The Artificial Hummingbird Algorithm (AHA) and its enhanced version (enAHA) are recently developed nature-inspired metaheuristic algorithms that mimic the intelligent foraging strategies and flight behaviors of hummingbirds [1]. Similar to other population-based methods, AHA aims to find a global solution by simulating a group of individuals (hummingbirds) searching for optimal food sources, which correspond to optimal fitness values. The algorithm is primarily characterized by three foraging strategies: guided, territorial, and migratory.

In AHA, the population of hummingbirds is represented by a matrix *pop* where each row corresponds to the position vector of a food source, containing the design variables of the antenna system. The foraging process is mathematically modeled using three flight patterns: axial, diagonal, and omnidirectional flight.

$$pop = \begin{bmatrix} v_{11} & v_{12} & v_{13} & \cdots & v_{1,ND} \\ v_{21} & v_{22} & v_{23} & \cdots & v_{2,ND} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ v_{NP,1} & v_{NP,2} & v_{NP,3} & \cdots & v_{NP,ND} \end{bmatrix} \quad (1)$$

The algorithm begins by creating the population of hummingbirds. Each hummingbird is assigned a random location vector with a dimension equal to the number of parameters of the problem. The value of each of the parameters is a random number within the boundaries set by the researcher. Moreover, a Visit Table is created, which serves as a "hummingbird memory". This table keeps track of which food sources (solutions) have been visited and favors the ones that haven't been visited recently. This promotes broader exploration of the solution space, helping to avoid local optima.

Initially, the fitness of each location vector is evaluated. At every subsequent iteration, the algorithm determines each bird's flight pattern. One of the three flight patterns is randomly selected.

- **Axial Flight:** Moves along one specific axis (changing only one parameter).
- **Diagonal Flight:** Moves along a few dimensions simultaneously.
- **Omnidirectional Flight:** Changes all parameters at once.

The algorithm then splits into two main behaviors of Foraging.

- During **Guided Foraging** , the bird identifies the best food source location that hasn't been visited recently, as tracked by the Visit Table. Moreover, the enhanced version of AHA takes advantage of the dFDB (DynamicFitnessDistanceBalance). This function calculates a score for other solutions based on both their fitness value and the distance from the current best. This causes the hummingbird's movement to be influenced not only by the Visit Table but also by the dFDB score, which prevents the bird from blindly following the leader, thus encouraging it to explore new regions of the search space.
- In the **Territorial Foraging** behavior, the hummingbird stays in its own territory, and it performs a local search around its current position. This is the exploitation phase, where the algorithm tries to fine-tune a design that is already looking promising.

Another foraging tactic that the algorithm takes into consideration is the "Migration Foraging". After a certain number of iterations, the algorithm identifies the worst-performing bird in the flock, resets it, and migrates it to a new random location. This assists the algorithm in escaping local optima.

Finally, the algorithm compares the new position to the old one. If the new antenna configuration is better, the hummingbird stays there, and the Visit Table is updated to show that its food location was used. If the new antenna is worse, the bird returns to its previous spot,but its visit counter is incremented, increasing the likelihood of it being selected by others in subsequent iterations.

III. Antenna Unit Design

In this work, we utilize the enAHA algorithm to obtain a feasible design solution for a dual-band IFA unit cell, which is subsequently integrated into a MIMO system. The IFA antenna is modified with an extra folded arm as shown in Fig.1. The operating frequencies fall within the 5G NR n78 band and the 5.8 GHz ISM band. The proposed antenna is designed on a Rogers RT/Duroid 5880 substrate layer, having a thickness of 1.575 mm and relative permittivity $\epsilon_r = 2.2$. The dimension of the substrate is $L_y = 10$ mm and $L_x = 40$ mm. In this particular design, the ground plane is set perpendicular to the antenna plane with dimensions $D_z = 1.575$ mm and $D_x = 40$ mm. This specific design consists of 9 geometric parameters.

TABLE I
Best values (feasible solution) of the antenna design parameters obtained by the ENAHA algorithm.

Parameter	Value (mm)	Parameter	Value (mm)
Arm len	4.95	*Width*	0.34
L_1	20.79	L_2	8.75
L_3	4.68	R_{con}	1.63
L_{con}	1.30	*Distance*	16.27
Arm offset	10.49	—	

Table I lists the best values (feasible solution) of the selected antenna design parameters obtained by the utilization of the enhanced hummingbird algorithm. The algorithm, implemented in MATLAB, was applied in conjunction with a custom HFSS-MATLAB-API and a commercial electromagnetic solver (Ansys Electronics Desktop 2025, © 2025 ANSYS, Inc.) to obtain a feasible solution of the proposed antenna. The objective function, which is to achieve a minimum value for the S_{11} parameter of the inverted-F antenna in the frequency bands mentioned above, applies the Min-Max method.

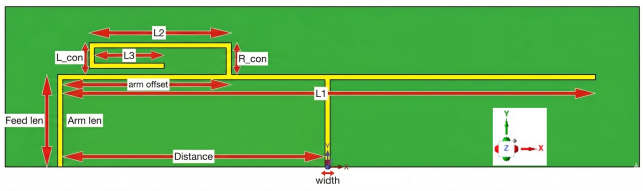

Fig. 1. Proposed geometry of IFA with folded arm. Ground plane is along the XZ plane.

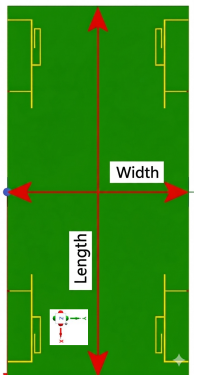

Fig. 2. Proposed geometry of the optimized MIMO antenna system.

The fitness function, defined in Eq. 2, employs a Min-Max approach to minimize the maximum return loss at the operating frequencies $f_1 = 3.55$ GHz and $f_2 = 5.80$ GHz. This ensures balanced performance by prioritizing the frequency of the poorest match. To strictly enforce the design requirement of $S_{11} < -10$ dB, a static penalty function is introduced. Here, $L_{target} = -10$ dB serves as the threshold, and Ψ represents a large penalty coefficient. The penalty term remains zero for compliant solutions and increases linearly when the return loss exceeds the defined threshold, effectively guiding the optimizer toward the feasible design space.

$$F = \underbrace{\max\left(S_{11}^{f_1}, S_{11}^{f_2}\right)}_{\text{Worst Case}} + \underbrace{\psi \sum_{k=1}^{2} \max\left(0, S_{11}^{f_k} - L_{target}\right)}_{\text{Penalty}} \tag{2}$$

The results for the reflection coefficient given by the optimal design were -23.57 dB for 3.55 GHz and -27.93 dB for 5.8 GHz, with a bandwidth of 100 and 500 MHz, respectively.

IV. MIMO Antenna Design and Numerical Results

The antenna element of Fig. 1 is used to construct a 4-element (2×2) MIMO antenna. The enAHA optimizer is again employed to determine the optimal inter-element spacing, ensuring isolation levels below -20dB for all S_{ij} parameters, while simultaneously keeping the occupation area as compact as possible.

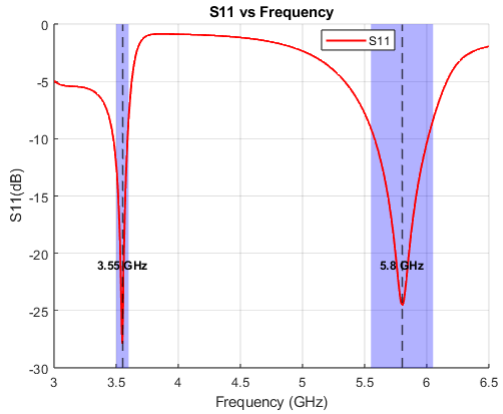

Fig. 3. Computed return loss of the proposed 4-element MIMO antenna in port 1.

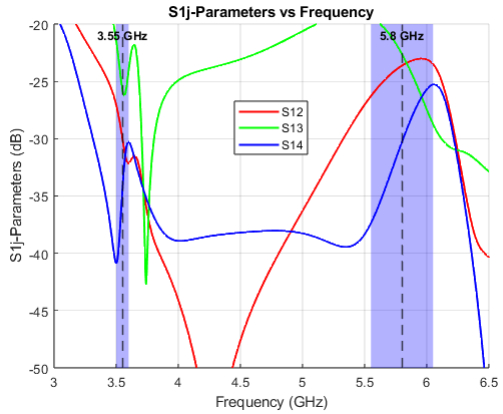

Fig. 4. Computed magnitude of S_{ij} parameters as a function of frequency for the proposed 4-element MIMO antenna.

Numerical results of the enAHA optimizer indicate that a feasible solution with high isolation and small size is achieved for a substrate with a width of 42 mm and a length of 87 mm. Subsequently, the distance between the feed ports of the antennas 1 and 2 (top left and bottom left antenna respectively in Fig. 2) is 47 mm, while between antennas 1 and 3 is 41.5 mm. Fig. 3 represents the computed return loss of the 4 antenna elements. The return loss for each port is basically the same because of the symmetry of the antenna elements, so S_{11} can represent each port. The computed magnitude of the S_{ij} parameters as a function of frequency is given in Fig. 4. From these two figures, it can be concluded that the antenna operates excellently in the two bands of interest with a very high isolation between the elements. Peak gain and radiation efficiency were also computed, with the antenna achieving an efficiency of around 87% and 99% and a gain of 2.63 dBi and 4.71 dBi for 3.55 GHz and 5.8 GHz bands, respectively.

In order to better estimate the performance of the proposed MIMO antenna, several key metrics must first be evaluated. Metrics such as the envelope correlation coefficient (ECC), the diversity gain (DG), and the total active reflection coefficient

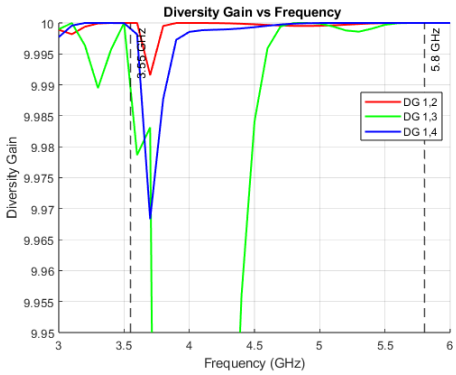

Fig. 5. Computed Diversity Gain of the proposed MIMO antenna.

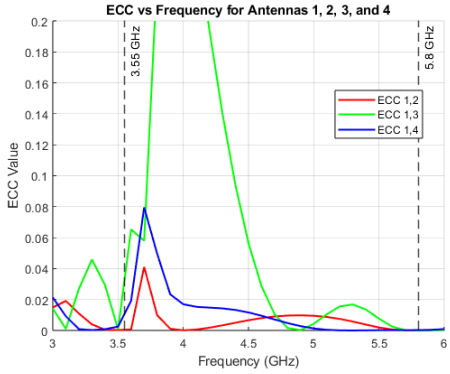

Fig. 6. Computed ECC of the proposed MIMO antenna.

(TARC) are meaningful to assess the performance of the MIMO antenna.

For a MIMO system to be considered effective for practical applications, these metrics should ideally fall within specific performance thresholds. The Envelope Correlation Coefficient (ECC), which measures the isolation and correlation between radiation patterns, should not exceed 0.5 per industry standards; however, for high-performance 5G applications, a value below 0.1 is preferred to ensure high channel capacity.

The Diversity Gain (DG) is directly related to the ECC and represents the improvement in signal-to-noise ratio. A theoretical maximum of 10 dB represents perfectly uncorrelated antennas; thus, a value exceeding 9.9 dB is typically targeted. Finally, the Total Active Reflection Coefficient (TARC) provides a more realistic measure of the antenna's return loss by accounting for mutual coupling when all ports are excited simultaneously. In practice, a TARC value below -10 dB is required within the operating bands to ensure efficient power radiation and minimal losses.

In Figs. 5, 6, and 7, the derived results confirm an excellent performance of the MIMO system across the two bands of interest. The worst-case ECC and DG values across the operating bands are 0.02 and 9.99 dB, respectively, both well within acceptable limits. Both metrics degrade around 4 GHz, but it is practically irrelevant, as it is outside the operating bands. The values of TARC are also very satisfactory

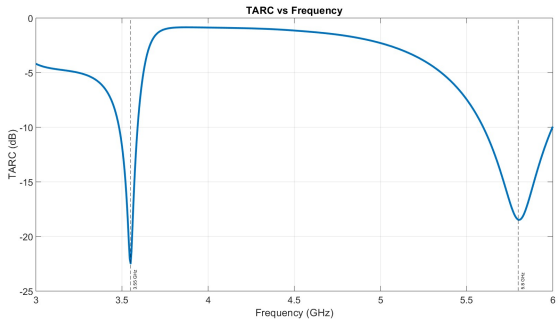

Fig. 7. Computed TARC of the proposed MIMO antenna.

as they are lower than -15 dB in both the operating bands.

V. Conclusion

In this work, we have designed and optimized a dual-band modified inverted-F antenna operating at 3.55 and 5.8 GHz. The antenna geometry was determined through the application of the enAHA. The size of the antenna element and the MIMO system is kept considerably small enough to be suitable for implementation in mobile phone terminals. Based on the presented numerical results, the proposed MIMO antenna demonstrates highly satisfactory performance in the aforementioned frequency bands of interest, and achieves high isolation and gain, while simultaneously accomplishing excellent MIMO performance. Future work includes the fabrication of a MIMO system implementing the same antenna element (20.8 mm $\times$ 7.26 mm) on the sides of a mobile phone terminal and its experimental validation.

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